12

CLIMATE CHANGE RESEARCH REPORT CCRR-12

Ontario's Forests and Forestry in a Changing Climate

Responding to Climate Change Through Partnership

Ontario

Climate Change and MNR: A Program-Level Strategy and Action Plan

The following describes how the Ministry of Natural Resources works to contribute to the Ontario Government's commitment to reduce the rate of global warming and the impacts associated with climate change. The framework contains strategies and sub-strategies organized according to the need to understand climate change, mitigate the impacts of rapid climate change, and help Ontarians adapt to climate change:

Theme 1: Understand Climate Change

Strategy #1: Gather and use knowledge in support of informed decision-making about climate change. Data and information gathering and management programs (e.g., research, inventory, monitoring, and assessment) that advances our knowledge of ecospheric function and related factors and forces such as climate change are critical to informed decision-making. Accordingly, MNR will work to:

- Strategy 1.A: Develop a provincial capability to describe, predict, and assess the important short- (0-5 years), medium- (5-20 years), and long-term (20+ years) impacts of climate change on the province's ecosystems and natural resources.
- Strategy 1.B: Model the carbon cycle.

Strategy #2: Use meaningful spatial and temporal frameworks to manage for climate change. A meaningful spatial and temporal context in which to manage human activity in the ecosphere and address climate change issues requires that MNR continue to define and describe Ontario's ecosystems in-space and time. In addition, MNR will use the administrative and thematic spatial units required to manage climate change issues.

Theme 2: Mitigate the Impacts of Climate Change

Strategy #3: Gather information about natural and cultural heritage values and ensure that this knowledge is used as part of the decision-making process established to manage for climate change impacts. MNR will continue to subscribe to a rational philosophy and corresponding suite of societal values that equip natural resource managers to take effective action in combating global warming and to help Ontarians adapt to the impacts of climate change.

Strategy #4: Use partnership to marshal a coordinated response [illegible]ate change. A comprehensive climate change program [illegible] sectors of society as partners and participants in decisi[illegible] processes. The Ministry of Natural Resources will work to [illegible]hat its clients and partners are engaged.

Strategy #5: Ensure corporate culture and function work in support of efforts to combat rapid climate change. Institutional culture and function provide a "place" for natural resource managers to develop and/or sponsor proactive and integrated programs. The Ministry of Natural Resources will continue to provide a "home place" for the people engaged in the management of climate change issues.

Strategy #6: Establish on-site management programs designed to plan ecologically, manage carbon sinks, reduce greenhouse gas emissions, and develop tools and techniques that help mitigate the impacts of rapid climate change. On-site land use planning and management techniques must be designed to protect the ecological and social pieces, patterns, and processes. Accordingly, MNR will work to:

- Strategy 6.A: Plan ecologically.
- Strategy 6.B: Manage carbon sinks.
- Strategy 6.C: Reduce emissions.
- Strategy 6.D: Develop tools and techniques to mitigate the impacts of rapid climate change.

Theme 3: Help Ontarians Adapt

Strategy #7: Think and plan strategically to prepare for natural disasters and develop and implement adaptation strategies. MNR will sponsor strategic thinking and planning to identify, establish, and modify short- and long-term direction on a regular basis. Accordingly, MNR will work to:

- Strategy 7.A: Sponsor strategic management of climate change issues.
- Strategy 7.B: Maintain and enhance an emergency response capability.
- Strategy 7.C: Develop and implement adaptation strategies for water management and wetlands.
- Strategy 7.D: Develop and implement adaptation strategies for human health.
- Strategy 7.E: Develop and implement adaptation strategies for ecosystem health, including biodiversity.
- Strategy 7.F: Develop and implement adaptation strategies for parks and protected areas for natural resource-related recreational opportunities and activities that are pursued outside of parks and protected areas.
- Strategy 7.G: Develop and implement adaptation strategies for forested ecosystems.

Strategy #8: Ensure policy and legislation respond to climate change challenges. Policy, legislation, and regulation guide development and use of the programs needed to combat climate change. MNR will work to ensure that its policies are proactive, balanced and realistic, and responsive to changing societal values and environmental conditions.

Strategy #9: Communicate. Ontarians must understand global warming, climate change, and the known and potential impacts in order to effectively and consistently participate in management programs and decision-making processes. Knowledge dissemination through life-long learning opportunities that are accessible and current is critical to this requirement. MNR will raise public understanding and awareness of climate change through education, extension, and training programs.

Ontario's Forests and Forestry in a Changing Climate

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Summary

This report updates a review of literature about the effects of global climate change on forest plants and communities published ten years ago (Forest Research Information Paper No. 143). Since the previous review, evidence of environmental changes caused by elevated atmospheric carbon dioxide (CO_2) and its potential effects on global climate has strengthened considerably, to the point that there are reports that the effects of climate change are already being observed. The International Panel on Climate Change (IPCC) indicates that rates of greenhouse gas emissions continue to increase due to fossil fuel burning and deforestation. Based on a less-than-worst-case scenario, the IPCC "A2" scenario, and modelled using the Canadian Global Climate Model (CGCM2), increased atmospheric CO_2 is projected to increase average summer temperatures in Ontario between 3°C and 6°C by 2070, with the largest increases in the far north but with heavily populated parts of the province warming by 4°C to 5°C. Growing season precipitation is predicted to increase only slightly (<10%) in much of Ontario, and to decrease in southern and northwestern Ontario. Projected increases in summer temperatures with no or little increase in precipitation would increase the frequency and severity of drought by elevating evapotranspiration.

One predictable response to drier forests is increased forest area burned. The projected increase is for a doubling of area burned in parts of the province where fire suppression is not practiced. In the managed forest, however, where more people live and where forests are more heavily used for timber production and recreation, most fires are currently able to be suppressed through early action. However, under severe fire weather conditions, initial attack at present can be unsuccessful, and climate change is expected to increase severe fire weather. As a result, an anticipated effect of climate change is increased frequency of uncontainable forest fire spread, resulting in more large burns in areas of managed forest.

The complex interactions of trees with insects and disease makes it difficult to project the timing and extent of effects of climate change on these disturbances. However, if drought increases tree stress, the occurrence and severity of insect and disease outbreaks are likely to increase. In addition to drought, extreme weather events, such as wind storms, flooding, and very high temperatures could stress plants and increase insect and disease outbreaks. As a result, most important diseases of Ontario trees are expected to increase, and none are anticipated to decline. Cold winters that have historically kept some insects out of Ontario will occur less frequently, resulting in possible expansions of their ranges. For example, mountain pine beetle, which in recent years expanded its range into boreal forests in northern Alberta, may reach Ontario's pine forests before 2050.

Climate change will increasingly make species and local populations of tree species less well adapted to the climate where they occur. For some species, this will reduce growth at the centre of their range and increase growth closer to the northern end of their distribution. The long lives of trees and their slow natural migration means that natural processes will be unable to move seed fast enough to match changing climate. Increasingly, forest managers will consider planting non-local species and populations. Such potential adaptations, however, need to be carried out with consideration of potential negative consequences and if implemented should be well documented and monitored.

Risks to forests from implementing adaptation strategies need to be weighed against the risks to forests if chosen actions affect current species biodiversity. For this reason, a coordinated, science-based approach to forest adaptation can help forest managers determine possible strategies for reducing the negative effects of climate change. This report describes an approach termed "judicious adaptation", in which risk of damage from implementing an adaptation is weighed against the risk of not acting. Adaptations carrying high risk would require strong evidence that failing to act creates an imminent threat. Low risk strategies would have a requirement for documentation of results to allow improved understanding of the risks and benefits of undertaking the adaptation. Judicious adaptation has similarities to the adaptive management approach, because of the requirements for planning and monitoring in both.

According to the IPCC, sustainable forest management that maintains forest carbon stocks and provides a sustained yield of wood products provides the best long-term climate change mitigation strategy for forests. Wood products from forests store carbon, but also can reduce greenhouse gas emissions from fossil fuels by using wood as an alternative energy source (either burned directly or burning methane generated by wood products in landfills). Solid wood products have considerably lower energy intensity than building materials such as steel, aluminum, brick, and concrete. Therefore, using wood in place of such other materials reduces emissions of greenhouse gases and is an indirect way that forests can contribute to mitigating climate change.

Résumé

Les auteurs du présent rapport actualisent une étude documentaire publiée il y a dix ans (*Forest Research Information Paper No. 143*) au sujet des effets du changement climatique sur les plantes et les communautés forestières. Depuis la rédaction du rapport précédent, les preuves de changements environnementaux causés par la forte concentration de gaz carbonique (CO_2) dans l'atmosphère et ses répercussions potentielles sur le climat de la Terre sont beaucoup plus évidentes, certains rapports indiquant que les effets du changement climatique sont déjà observables. Le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) fait valoir que les taux d'émission de gaz à effet de serre continuent d'augmenter en raison de l'emploi de combustibles fossiles et de la déforestation. Selon le scénario « A2 » du GIEC, négatif sans toutefois être le plus pessimiste, et le modèle canadien de circulation générale (MCCG2), la concentration accrue de CO_2 dans l'atmosphère pourrait faire monter les températures estivales moyennes en Ontario de 3 à 6 °C d'ici 2070 : les variations les

plus importantes seraient observées dans l'Extrême Nord, mais les endroits très peuplés de la province se réchaufferaient de 4 à 5 °C. Les précipitations en saison de croissance ne devraient augmenter que légèrement (< 10 p. 100) dans la plus grande partie de l'Ontario, mais diminuer dans le Sud et le Nord-Ouest de la province. Les hausses de température estivale prévues combinées à une augmentation faible ou nulle des précipitations rendraient les sécheresses plus fréquentes et plus graves du fait d'une évapotranspiration accrue.

L'une des conséquences prévisibles de cet « assèchement » des forêts est l'expansion de la superficie de forêts brûlées, qui pourrait doubler dans certaines parties de la province où la suppression des incendies n'est pas pratiquée. Par contre, dans les forêts gérées, habitées par un plus grand nombre de personnes et utilisées de façon beaucoup plus importante pour la production de bois d'œuvre et les loisirs, la plupart des incendies peuvent à l'heure actuelle être étouffés grâce à une intervention précoce. Cependant, lorsque les conditions météorologiques entraînent un risque élevé d'incendie, l'intervention initiale peut présentement s'avérer infructueuse, et la fréquence de telles conditions augmentera vraisemblablement en raison du réchauffement climatique. Par conséquent, un des effets attendus du changement climatique est la fréquence accrue des incendies de forêt incontrôlables, ce qui entraînera des brûlis plus importants même dans les zones forestières gérées.

En raison de l'interaction complexe des arbres avec les insectes et les maladies, il est difficile de prévoir à quel moment se feront sentir les effets du changement climatique sur ces perturbations et l'ampleur qu'ils prendront. Toutefois, les arbres affaiblis par la sécheresse seront probablement plus vulnérables aux insectes et aux épidémies. Outre la sécheresse, les phénomènes météorologiques extrêmes tels que les tempêtes de vent, les inondations et les vagues de chaleur pourraient nuire aux plantes et favoriser les invasions d'insectes et les épidémies. Par conséquent, la plupart des maladies importantes qui affectent les arbres de l'Ontario devraient se manifester plus souvent ou, à tout le moins, ne diminuer aucunement. Les hivers froids qui, traditionnellement, protégeaient l'Ontario de certains insectes se feront de plus en plus rares, et n'empêcheront plus ceux-ci d'étendre leur territoire de répartition. Par exemple, le dendroctone du pin ponderosa, que l'on trouve depuis peu d'années dans les forêts boréales du Nord de l'Alberta, risque d'envahir les pinèdes de l'Ontario avant 2050.

À mesure que le climat se réchauffera, les espèces et les peuplements indigènes d'essences forestières deviendront de moins en moins bien adaptés à leur environnement naturel. Pour certaines espèces, cela se traduira par une croissance réduite au centre de leur territoire de répartition et accrue à l'extrémité nord de celui-ci. Parce qu'ils vivent longtemps et suivent une lente migration naturelle, les arbres seront de plus en plus mal adaptés à leur milieu et les procédés naturels ne parviendront pas à en déplacer les semences aussi rapidement qu'il le faudrait pour suivre le rythme du changement climatique. Les aménagistes forestiers envisageront de plus en plus de planter des essences et des peuplements non indigènes. De telles adaptations ne pourront toutefois être décidées sans qu'il soit tenu compte de leurs conséquences négatives possibles et devront être documentées et surveillées étroitement.

Pour les forêts, les risques associés à la mise en œuvre de stratégies d'adaptation devront être comparés à l'incidence que les mesures choisies pourraient avoir sur la biodiversité actuelle des espèces. C'est pourquoi une approche scientifique coordonnée en matière d'adaptation des forêts peut aider les aménagistes forestiers à déterminer les stratégies possibles permettant d'atténuer les effets négatifs du changement climatique. Le présent rapport décrit une approche appelée « adaptation judicieuse », selon laquelle le risque de dommage lié à la mise en œuvre d'une adaptation est comparé au risque qu'entraînerait l'inaction. Les adaptations présentant un risque élevé devraient ainsi être appuyées par des preuves démontrant hors de tout doute que l'absence d'intervention poserait une menace imminente. Dans le cas des stratégies à faible risque, une documentation des résultats serait exigée pour permettre une compréhension accrue des avantages et des inconvénients de l'adaptation. L'adaptation judicieuse comporte des similitudes avec la gestion adaptative, les exigences de planification et de surveillance étant les mêmes dans les deux cas.

Selon le GIEC, une gestion forestière durable qui maintient les stocks de carbone forestier et procure un rendement soutenu en matière de produits du bois constitue la meilleure stratégie à long terme d'atténuation du changement climatique pour les forêts. Les produits du bois des forêts emmagasinent le carbone, mais peuvent également réduire les émissions de gaz à effet de serre provenant des combustibles fossiles s'ils sont substitués à ceux-ci comme source d'énergie (en brûlant directement le bois ou en brûlant le méthane généré par les produits du bois enfouis dans les décharges). Les produits en bois massif ayant une intensité énergétique beaucoup plus faible que les matériaux de construction tels que l'acier, l'aluminium, la brique et le béton, la substitution de ces matériaux par le bois réduit les émissions de gaz à effet de serre et représente une façon indirecte dont les forêts peuvent contribuer à modérer le changement climatique.

Les forêts sont présentement gérées en fonction d'un paradigme de climat constant, qui suppose implicitement que le climat demeurera inchangé. Puisque de nombreuses décisions prises aujourd'hui en matière de foresterie auront une incidence sur les forêts dans 50 ans et plus, une transition vers des politiques et des pratiques qui reconnaissent les effets potentiels du changement climatique s'impose. Pour permettre l'élaboration de telles politiques et pratiques, les chercheurs doivent répondre aux besoins de la gestion forestière pratique en améliorant notre connaissance de la réaction des forêts à leur environnement et en concevant des modèles qui utilisent ces renseignements pour prévoir l'état futur des forêts selon diverses conditions climatiques possibles.

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The Changing Climate

Through industrial activity and tropical deforestation, humanity is on a path to emit enough greenhouse gas into the atmosphere to cause the planet to warm to temperatures not seen in the past 100,000 years (Figure 1, IPCC 2007a). Although Earth has experienced similar amounts of natural warming in the distant past, the rate of these past warmings has been much, much slower (Figure 1). No area of the planet and no plant or animal will avoid the effects of climate change. That humanity could be rapidly changing future global climate sounds like science fiction, but scientists assert that this change will occur unless greenhouse gas emissions and tropical deforestation are reduced (IPCC 2007a).

Under this scenario of rapid ecological change, natural resource managers must determine what the impacts could be and how best to manage. Will trees grow faster or slower? Will wildlife species migrate north as temperatures warm? Will warmer temperatures cause more forest fires? Such questions are important to understanding how to manage forests sustainably today when the risk is high that the future climate may be very different.

The International Panel on Climate Change (IPCC) predicts that the greenhouse gases expected to enter the atmosphere will cause the average temperature of northern North America to increase by 1.4°C-5.8°C this century (IPCC 2007a). The lower end of this range, a 1-2°C increase in global temperature, might not seem alarming, since in the course of every day we see far greater changes in temperature. Even a 5-6°C increase in temperature may not seem significant. However, a 1-2°C increase is an average for the entire planet, and changes in temperature in some areas and at some times of the year will be much greater than the average global change. This means that at high latitudes and during winter, temperatures will warm more than at low latitudes and during summer. In addition, extreme events are expected to increase, as higher temperatures indicate more energy is in the atmosphere. As a result, more floods will occur due to more intense rainfall, more windstorms, and more tornadoes (IPCC 2007a).

The rate of temperature change from human-caused global warming will be much greater than has occurred over the past 400,000 years. The circled area of the left graph in Figure 1, for example, shows a large temperature increase that occurred between 100,000 and 150,000 years ago, when global average temperature increased by about 3.3°C over 2,400 years. At current rates of greenhouse gas emissions, Earth will experience at least this increase in global temperatures, but the change will happen over only about 75 years.

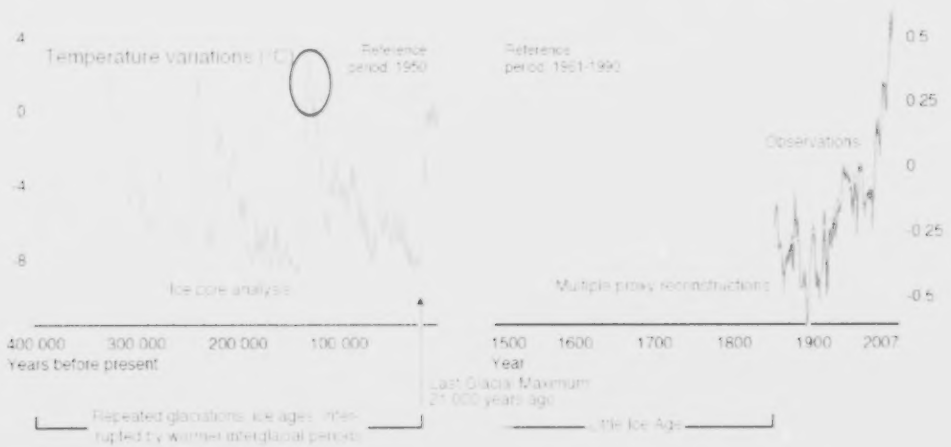


Figure 1. *Historical trends in annual global average temperature on a geological and recent time scale. The y-axis scale of the right graph is from -0.5°C to +0.5°C, while the left graph has a y-axis scale 16 times as large, ranging from -12°C to +4°C. The periodic warming shown in the left graph occurs over thousands of years, while recent warming shown at the right occurs over tens of years. The circled portion of the left graph shows warming of about 4°C over about 2,400 years.* (From: NEP/GRID-Arendal, Historical trends in carbon dioxide concentrations and temperature, on a geological and recent time scale, UNEP/GRID-Arendal Maps and Graphics Library, June 2007, <http://maps.grida.no/go/graphic/historical-trends-in-carbon-dioxide-concentrations-and-temperature-on-a-geological-and-recent-time-scale> [Accessed 17 December 2007]).

Climate Change in Ontario

The Ontario Ministry of Natural Resources (MNR) and Natural Resources Canada produced a publication containing maps based on climate simulations from the Canadian Global Climate Model (GCM) for 2 intermediate scenarios of future climate (A2 and B2) based on differing amounts of greenhouse gas emissions (Colombo et al. 2007b). The CD accompanying the report provides about 800 maps, showing Ontario climate at different times and geographic scales (province, MNR administrative region, and MNR district). In Figures 2-4 here, we show maps from Colombo et al. (2007b) of average summer temperature, average winter temperature, and total warm season precipitation (April-September) projections for the period 2071-2100, based on the A2 scenario.

Across the province, warming is projected to be greater in winter than summer and greater in the north than the south (figures 2 and 3). In the Far North, including the communities of Fort Severn, Kashechwan, and Sandy Lake, summer temperatures are projected to increase 5-6°C. In much of the rest of Ontario, summer temperature will increase 4-5°C. In 2071-2100, Kenora summer temperatures will be similar to those of present-day Windsor, while Windsor will experience summers about as hot as present-day Virginia.

Under the A2 scenario, winters for people living near Hudson Bay are projected to be 9-10°C warmer by 2071, and most of northern Ontario will warm by 6°C or more (Figure 3). This means people in northern parts of the region will experience winter temperatures comparable to those hundreds of kilometres further south in 1971-2000. For example, by 2070 winter temperatures:

- In Thunder Bay will be more like those in Peterborough
- The area running from Sault Ste. Marie east to Espanola and North Bay will warm 4-5°C (Figure 3)
- In most of southern Ontario, will warm 4-5°C (cities such as Barrie, Brockville, and Parry Sound will have mild winters like those of Windsor today)
- In the already-mild Golden Horseshoe, plus Sarnia and Chatham, winters will be more like those currently in southern Ohio and Indiana.

Precipitation is projected to change as well. By about 2011, precipitation in much of northwestern Ontario is projected to decrease by up to 10%. By 2071 in an A2 world, almost the entire western half of northwestern Ontario and much of southern Ontario will receive up to 10% less precipitation (Figure 4).This change, along with higher temperatures, will result in considerably drier soils and forests. Under this scenario, most of northern Ontario is projected to receive about the same or slightly higher precipitation in 2071, but even in these areas soils will be considerably drier due to higher temperatures.

In addition to changes in climate, at current rates of greenhouse gas emissions, the concentration of CO_2 in the atmosphere will more than double by mid-century and triple by the end of the century from a pre-industrial level of about 280 ppm. The last time the atmosphere contained over 500 ppmv CO_2 is estimated to have been about 50 million years ago, and CO_2 levels of 800 ppm have not been found on Earth since between 75 million and 100 million years ago (Fletcher et al. 2008). Carbon dioxide is the chief culprit in anthropogenic climate change and the primary food source for plants. Changes in atmospheric CO_2 levels directly affect photosynthesis and therefore plant growth rates, water and nutrient use, competitiveness, and stress resistance. Under increased CO_2 all species will be more resistant to drought and, given adequate moisture and nutrient supply, will likely grow more quickly; however, it is unclear how interactions among species will change and how insect herbivores will respond (Mousseau and Saugier 1992, Karnosky 2003, Körner 2006).

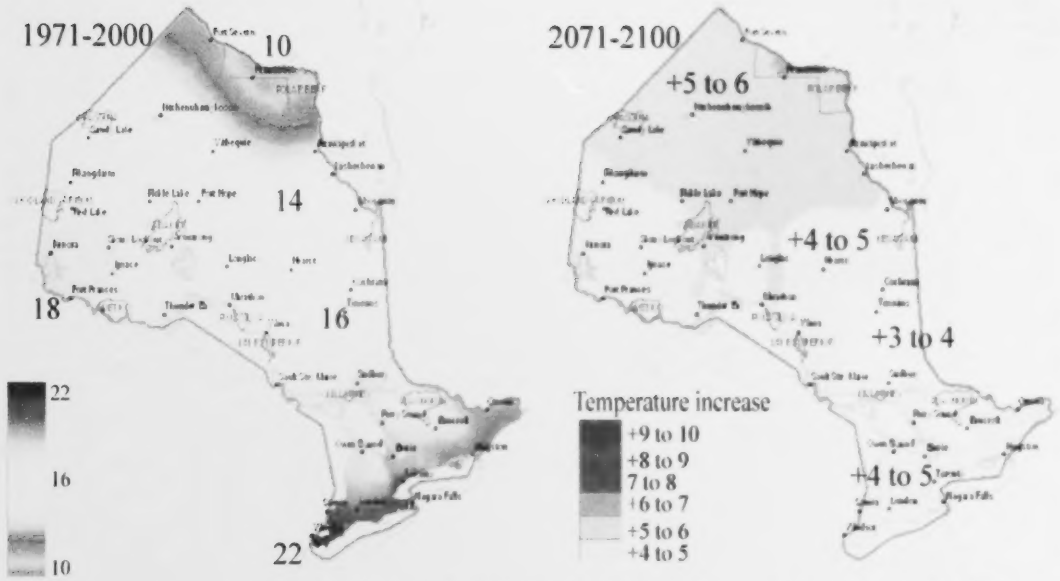


Figure 2. *Average summer temperature in Ontario from 1971-2000 (left) and projected increases in summer temperature in 2071-2100 (right), based on the Canadian Global Climate Model and the A2 greenhouse gas scenario (Colombo et al. 2007b). Numbers on maps refer to temperatures (°C) in the case of 1971-2000 and increases in temperature (°C warming) in the case of 2071-2100.*

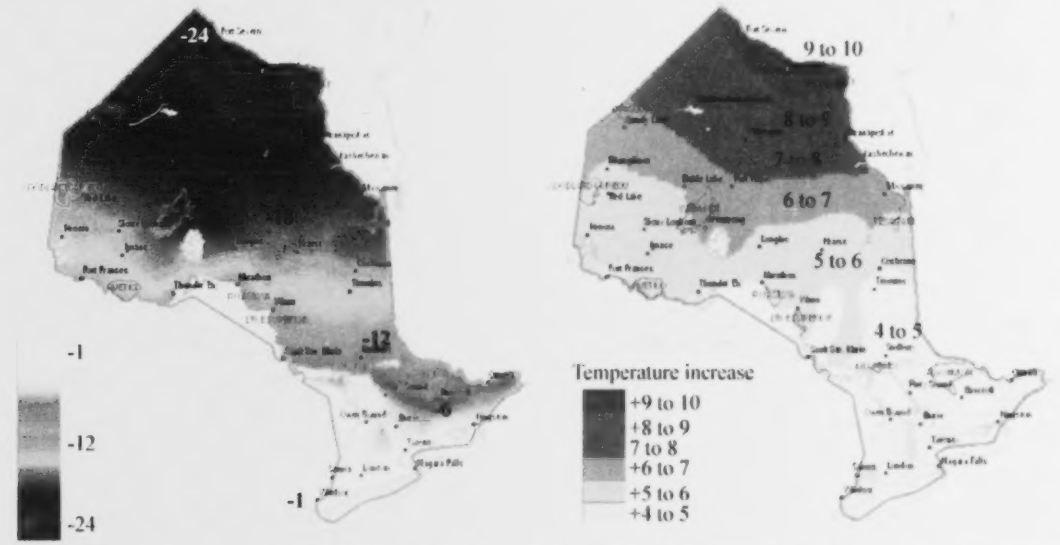
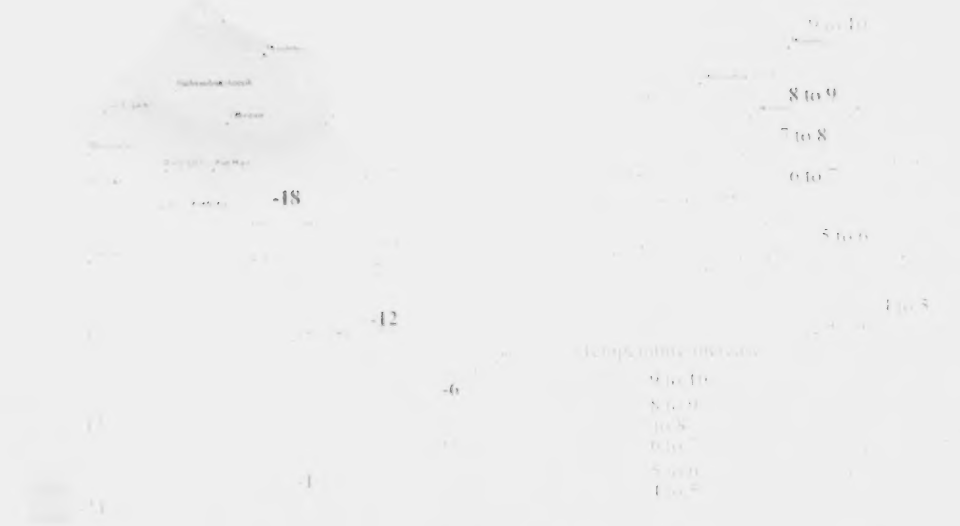


Figure 3. *Average winter temperature in Ontario from 1971-2000 (left) and projected increases in winter temperature in 2071-2100 (right), based on the Canadian Global Climate Model and the A2 greenhouse gas scenario (Colombo et al. 2007b). Numbers on maps refer to temperatures (°C) in the case of 1971-2000 and increase in temperature (°C warming) in the case of 2071-2100.*

1971-2000
2071-2100
4 to 5
3 to 4


8 to 9
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-18
-12
-6

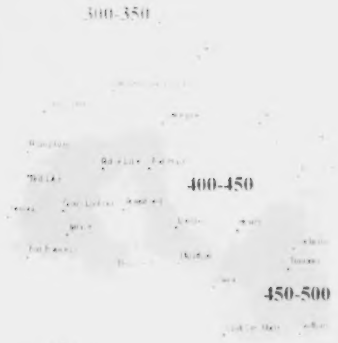

Figure 4

Forest Management and Climate

Many researchers are already seeing the effects of climate change (Parmesan 2006). In all ecosystems (terrestrial, marine, freshwater), changes in the timing of temperature-driven events (such as bud burst, flowering, breaking hibernation, migration, breeding) and the distributions of plant and animal species are heading in the direction that climate change experts predicted (Parmesan 2006). In 2006, 10 eminent forest scientists from the United States, Russia, and Canada found substantial evidence that boreal forests are already responding to climate change (Soja et al. 2007). There are two important implications from their conclusions. The first is that although change in boreal climate has to now been slight, the response is readily observable, suggesting that the boreal forest is relatively sensitive to climate change. The second implication is that with comparatively large changes in climate in coming decades, the response may be more substantial than previously projected.

Two recent surveys of forestry professionals have shown that most recognize the serious effects climate change could cause and the need to adapt (Williamson et al. 2005, Colombo 2006). Even so, forest management decision-making is still based on the assumption of a stable climate, whether the issue is where to plant what species, which genetic sources to use, and how much to harvest, which is based on how quickly forests have grown in the past. If forestry professionals' attitudes have changed, why hasn't forest management decision-making? Some possible reasons include:

1. Much forest management knowledge in use today is based on past behaviour of forests, which is not correlated with climate and therefore is difficult to extrapolate to new climate conditions.
2. It is not certain how quickly and how much the temperature will increase and whether growing season precipitation will be adequate.
3. Information is lacking about how forests respond to climate, including growth rates of trees and sensitivity of forest succession.
4. The lack of climate change policies may be creating uncertainty about the acceptability of implementing adaptations.

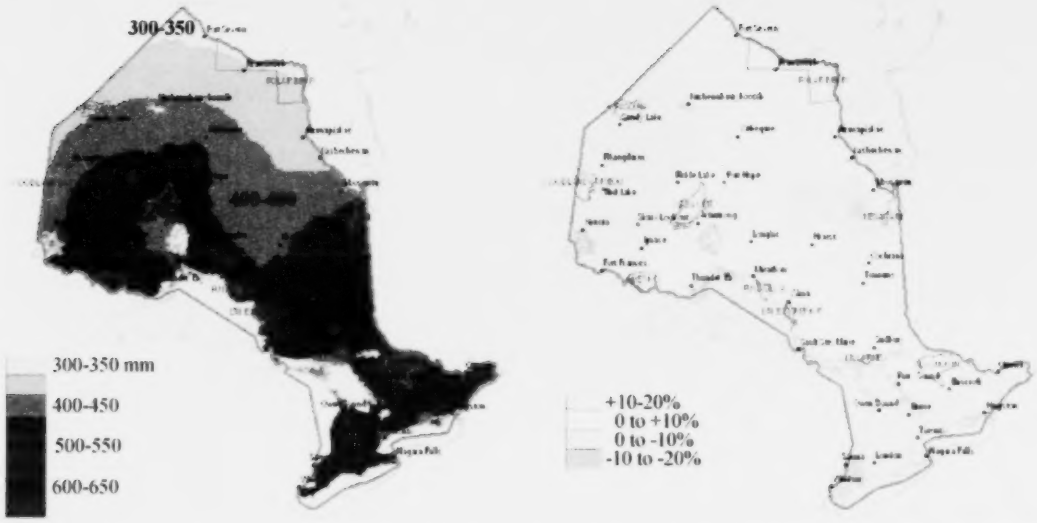

Figure 4. *Total warm season precipitation in Ontario from 1971-2000 (left) and projected changes in warm season precipitation in 2071-2100 (right), based on the Canadian Global Climate Model and the A2 greenhouse gas scenario. Numbers on maps of 1971-2000 precipitation refer to millimetres of total precipitation received April-September; scale values for 2071-2100 are the percent change in total warm season precipitation compared with 1971-2000 (Colombo et al. 2007b).*

Forest Management and Climate

Many researchers are already seeing the effects of climate change (Parmesan 2006). In all well-studied ecosystems (terrestrial, marine, freshwater), changes in the timing of temperature-driven events (such as bud burst, flowering, breaking hibernation, migration, breeding) and the distributions of plant and animal species are heading in the direction that climate change experts predicted (Parmesan 2006). In 2006, 10 eminent forest scientists from the United States, Russia, and Canada found substantial evidence that boreal forests are already responding to climate change (Soja et al. 2007). There are two important implications from their conclusions. The first is that although change in boreal climate has to now been slight, the response is readily observable, suggesting that the boreal forest is relatively sensitive to climate change. The second implication is that with comparatively large changes in climate in coming decades, the response may be more substantial than previously projected.

Two recent surveys of forestry professionals have shown that most recognize the serious effects climate change could cause and the need to adapt (Williamson et al. 2005, Colombo 2006). Even so, forest management decision-making is still based on the assumption of a stable climate, whether the issue is where to plant what species, which genetic sources to use, and how much to harvest, which is based on how quickly forests have grown in the past. If forestry professionals' attitudes have changed, why hasn't forest management decision-making? Some possible reasons include:

1. Much forest management knowledge in use today is based on past behaviour of forests, which is not correlated with climate and therefore is difficult to extrapolate to new climate conditions.
2. It is not certain how quickly and how much the temperature will increase and whether growing season precipitation will be adequate.
3. Information is lacking about how forests respond to climate, including growth rates of trees and sensitivity of forest succession.
4. The lack of climate change policies may be creating uncertainty about the acceptability of implementing adaptations.

Uncertainty about future climate and forests' potential responses to climate change mean that adapting to climate change should be done with care, as such actions carry risks. However, given how quickly climate change may occur, delaying action is also risky.

More than 40 years ago, U.S. Forest Service pathologist George Hepting acknowledged the need to adapt to climate change and described how global climate change might affect forests and forestry in North America (Hepting 1963). Over the intervening decades, forest research has not sufficiently addressed climate change impacts and adaptation to provide forest managers tools to allow them to plan to adapt. While exceptions exist, research on climate change impacts on forests has been conducted mostly in the past decade. As a result, we still have much to learn about adapting forests to climate change.

McLachlan et al. (2007) have developed a framework for assisted migration, which I have applied to the more general issue of adapting to climate change. They identified three positions that demonstrate the contrasting risks of acting vs. not acting on adaptation: aggressive adaptation, adaptation avoidance, and judicious adaptation.

Aggressive adaptation is based on the concern that climate change presents an immediate threat to ecosystems. Supporters of aggressive adaptation assume that climate is critical to ecosystem behaviour, projections of climate change impacts on forests are accurate, and forests will not naturally adapt to avoid severe climate change effects. They also believe that time to implement adaptation is short and that it is not possible to predict all impacts on all ecosystems. Management strategies include moving species well beyond native ranges and shortening harvest cycles to remove stands considered at risk of decline and whose regeneration presents an opportunity for adaptation. This policy may be the preferred option to avoid harmful effects on forests due to devastating and rapid climate change, but it could place existing forest values at higher risk of disruption.

In contrast, advocates of *adaptation avoidance* believe that human interference could have unintended consequences in natural systems, given the great uncertainty in ecological understanding of climate-forest interactions. The lag between implementing a new strategy and potential negative effects can sometimes be decades long, so monitoring negative impacts may be impractical. Proponents of adaptation avoidance are motivated by the high uncertainty about future climate projections and the similar if not greater uncertainty about ecosystem responses to climate change. Avoiding adaptation could greatly increase the risk of severe climate change impacts on forests. Where active adaptation is avoided, forest managers should encourage policies that facilitate adaptation by natural processes. For example, they could allow natural disturbance to increase or rely more on the intense selection pressure from natural regeneration by seed, instead of planting trees from local seed.

The third strategy outlined by McLachlan et al. (2007), *judicious adaptation*, balances risks from unrestrained adaptation and adaptation avoidance. It is based on the belief that some (but not all) adaptation actions are warranted despite their risks. In a judicious framework, risk is reduced by restricting what actions can be taken, carefully planning their implementation, and closely monitoring their results. This planning-monitoring approach has similarity to adaptive forest management. One approach would be to consider potential actions using a framework for incorporating climate change adaptation in forest management, such as the one developed by Ogden and Innes (2007). Specific adaptation options could be developed by multi-disciplinary panels of local experts and scientists (McLachlan et al. 2007) and prioritized in terms of risk (high, moderate, low) and geographic scale (large, medium, small).

Presumably, climate change adaptation proposals carrying high risk would require a strong case showing the need to act promptly to avoid an imminent threat. The potential spread of mountain pine beetle into northwestern Ontario is an example of a threat that could cause forest managers to consider implementing a relatively high risk adaptation strategy. To consider acting on even moderate-risk proposals would require strong evidence of benefit and even stronger evidence of risks of inaction. Decisions would be made by balancing respect for the precautionary principle and the need for pilot projects to improve understanding of the risks and benefits of implementing adaptations. This cautious approach would likely be relaxed as uncertainty about future atmospheric greenhouse gas levels is reduced; improvements in GCMs reduce the uncertainty of global climate projections; forest scientists provide better tools to predict the outcomes of adaptation; and forest managers gain experience with implementing adaptations.

Climate and Natural Forest Disturbances

Increased frequency, intensity, and geographic extent of natural disturbance are expected to be some of the most obvious and immediate effects of climate change on forests (Pollard 1989, Flannigan et al. 2005). Insects and diseases are sensitive to climate and should provide some of the earliest visible impacts of climate change (Pollard 1989). The massive outbreak of mountain pine beetle in western Canada is a prime example of how warmer winters can favour insect pests. Pests and disease also increase fuel loads, indirectly increasing the area burned by forest fires (Pollard 1989).

Forest Fire

Predictions of how climate change may alter fire frequency, intensity, and area burned is based in part on empirical relationships between past climate and fire disturbance (e.g., Flannigan and Harrington 1988). Altered precipitation and temperature across North America will change fire risk, with some areas experiencing greater risk and other areas less (Flannigan et al. 2000, Dale et al. 2001). Climate warming is expected to increase the length of Ontario's fire season in Ontario by up to 16% or 25 days (Wotton and Flannigan 1993). Higher summer temperatures increase evaporation and transpiration and dry out forest soils, dead trees, and downed wood. These changes increase the risk of forest fire, even when precipitation does not decrease.

Future fire risk was projected by Flannigan et al. (2000) using 2 GCMs and a seasonal fire weather severity rating model. Higher seasonal severity ratings yield greater area burned. With a doubling of CO_2, the Canadian GCM projects an increase >30% in the average seasonal severity rating for the southeast United States and Alaska and most of Canada north of the 48th parallel (Flannigan et al. 2000). This model also predicts increased seasonal severity rating of 40% or more in much of northwestern Ontario and northern Manitoba. According to both the Canadian and Hadley GCMs, a tripling of CO_2 later in the 21st century would increase area burned in Ontario's forests by 1.5 to more than 2.0 times, with greater increases in more northerly parts of the province (Flannigan et al. 2005). Large fires tend to be uncontrollable, and large fires will increase under climate change (McAlpine 1998).

Present-day area burned in Ontario's managed forest is relatively low, reflecting high initial fire attack success rates (Ward et al. 2001). However, more severe fire weather may create fire spread conditions making initial attack less successful (Flannigan et al. 2005) and result in more large burns. Large increases in forest area burned would change biodiversity to reflect more fire-origin stands and younger average forest age (Weber and Flannigan 1997).

Insect Outbreaks

Predicting how climate change might affect forest insect infestations is difficult because insect populations depend on relationships with hosts, competitors, predators, and symbiotes (Williams et al. 2000). For this reason, modelling is often used to describe the effects of climate change on insect populations. Direct effects of climate change on insect herbivores will be through insect growth, development, and reproduction (Williams et al. 2000). Since many insects can produce multiple generations in a year, even a small increase in growing season temperature could add a generation, increasing the potential for damage to trees (Williams et al. 2000). Climate change can also affect insects indirectly by altering host plant physiology and predator behaviour (Williams et al. 2000).

Fleming and Candau (1998) predicted that disturbance patterns of insects whose distributions depend largely on climate will likely change greatly under projected climate warming. Northern range limits for many insect herbivores are based on their ability to survive low winter temperatures; as the climate warms, ranges should move northward (Parker et al. 2000, Williams et al. 2000).

Pollard (1989) predicted the extremely high risk of an outbreak of mountain pine beetle (*Dendroctonus ponderosae*) in British Columbia, and the recent extensive outbreaks of mountain pine beetle in British Columbia are attributed to milder winter temperatures (Pollard 1989, Dale et al. 2001). Cumulative lodgepole pine (*Pinus*

contorta Dougl.) mortality in British Columbia's timber harvesting land base from 1998 to 2006 was approximately 530 million m^3, representing 40% of the total merchantable volume of pine, and by 2014, nearly 80% of the province's lodgepole pine may be killed (Walton et al. 2007). The outbreak has spread extensively in northern Alberta's boreal forest, with aerial recognition of affected stands as far east as Swan Hills (http://www.srd.gov.ab.ca/forests/health/conditionsmaps/mpbcurrentmaps.aspx, viewed December 21, 2007). The mountain pine beetle is also favoured by higher summer temperatures and moisture stress, conditions projected to become more common in boreal forests in Saskatchewan, Manitoba, and northwestern Ontario. Thus, it is now likely a question of *when* the mountain pine beetle will migrate into Ontario, not *if* migration will occur (Logan and Powell 2001, Logan et al. 2003). Logan and Powell (2001) projected migration of mountain pine beetle to Ontario by 2050. The rapid spread of this beetle east into Alberta may indicate that it could reach Ontario much sooner than projected.

Climate change can affect defoliating insects that feed on newly expanding leaves, since they need to hatch when bud burst occurs. Warmer spring temperatures in Europe have reduced defoliation of English oak (*Quercus robur* L.) as the hatching of the winter moth (*Operophtera brumata* L.) is no longer tightly synchronized with bud burst (Visser and Holleman 2001). In addition, drought can delay budburst (Colombo, unpublished) and thus cause insects to hatch before the optimum time for feeding. Even a few days difference in the timing of caterpillar emergence or new shoot elongation can cause insects to starve (Williams et al. 2000). In the same way, asynchrony of parasitoids with their insect hosts, which provide some natural control of pest insect levels, may increase or decrease as the climate changes (parasitoids are insects whose larvae develop within or on other insects, eventually killing the host).

Williams et al. (2000) speculate how climate change may affect the major insect pests of trees in the northern United States. Warmer wetter summers would favour vigorous shoot growth of white pine (*Pinus strobus* L.), which in turn would favour the white pine weevil (*Pissoides strobi* Peck). Increased water stress would favour the spruce beetle (*Dendroctonus rufipennis* Kirby) and in a warmer climate could complete its life cycle in 1 year rather than 2. Warmer temperatures may also allow the hemlock woolly aphid (*Adelges tsugae* Annand) to produce another generation annually, to survive better during milder winters, to begin activity earlier in the spring, and to spread further north (Williams et al. 2000). Fleming and Candau (1998) conclude that while climate change will likely alter the severity of spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks, predicting the likelihood of such changes remains difficult.

Disease

Geographic patterns of most historical disease outbreaks are poorly understood. Exceptions occur when alien diseases affect native tree species, causing relatively rapid and extensive losses of prominent species, such as Dutch elm disease (*Ophiostoma ulmi* (Buisman) Nannf.) and chestnut blight (*Cryphonectria parasitica* (Murrill) M.E. Barr). Losses caused by most native diseases are usually difficult to identify, as they tend to affect scattered trees or pockets of trees, and even foresters find it difficult to relate mortality to disease. As a result, climate-disease interactions are often unclear, and disease effects often go unrecognized.

Disease occurs when interactions among host, pathogen, and environment favour the pathogen (Williams et al. 2000). In general, where climate change increases tree stress in the presence of a pathogen, disease increases. Trees growing in marginal environments may be more susceptible to disease if climate change increases environmental stress (Coakley et al. 1999). Trees now exposed to intermittent summer drought because they are in dry habitats may be more prone to disease if climate change further reduces soil moisture. For example, *Armillaria* spp. root rot may increase where drought becomes more common (Coakley et al. 1999, Williams et al. 2000), and heat stress may boost the occurrence of Scleroderris canker (*Gremmeniella abietina* (Lagerb.) M. Moreleton) on pine (Coakley et al. 1999).

On the other hand, some species may experience less disease if environmental stress is reduced (e.g., trees growing near their northern limit that often experience freezing stress may benefit from a warming climate). Increased temperature extremes and droughts, rather than changes in average temperature or precipitation, are likely to favour diseases (Boland et al. 2004), with disease becoming evident sometimes long after the stress. Latent pathogens (parasitic disease organisms that can lay dormant until a tree becomes stressed) may kill

individuals weakened by drought (Desprez-Loustau et al. 2006). Increased drought, a possible outcome of climate change for some parts of Ontario (Colombo et al. 2007b), could contribute to "decline" diseases in tree species.

Whether diseases expand into new regions is determined by their method of dispersal, the suitability of the environment (especially winter weather), and host species physiology (Coakley et al. 1999). Climate matching models (e.g., BIOCLIM, CLIMEX, HABITAT, and WORLD) have been used to predict changes in pathogen ranges based on future climate (Williams et al. 2000). Generally, wetter conditions increase the incidence and severity of foliar and root pathogens that depend on higher moisture levels to develop and disperse (Williams et al. 2000). Seem et al. (2000) developed a model predicting surface wetness duration, a critical factor in the spread of many diseases, including white pine blister rust (*Cronartium ribicola* J.C Fischer). Applying such a model to Ontario could allow susceptibility of white pine to blister rust to be projected with future climate change.

Elevated winter temperatures will increase the spread of dormant season pathogens, such as stem canker fungi, whose growth is limited by winter cold. Snow moulds, requiring humid but not extreme cold under snowcover, may increase in some areas but decrease where snowfall decreases (Williams et al. 2000). Boland et al. (2004) summarized the potential effects of climate change on tree diseases in Ontario. They project that climate change will increase the incidence of decline diseases of maple, oak and ash; beech bark disease (*Nectria coccinea* (Pres.:Fr.)Fr. var. *faginata* Lohman, Watson & Ayers); oak wilt (*Ceratocystis fagacearum* (Bretz) Hunt); *Armillaria* root rot (*Armillaria ostoyae* (Romagn.) Herink); blue stains; *Diplodia* canker; *Fomes* root rot (*Heterobasidion annosum* (Fr.:Fr.) Bref.); *Hypoxylon* canker; and *Tomentosus* root rot (*Inonotus tomentosus* (Fr.: Fr.) Teng). They do not expect any tree disease in Ontario to decline with climate change.

Hurricanes can rapidly spread insects and insect-borne diseases, and they are expected to increase under climate change (Dale et al. 2001). In the early 1950s, hurricanes may have helped spread elm bark beetles into eastern Canada (Hepting 1963). The rapid and long-scale movement of insect-borne diseases by hurricanes, combined with forests' increasing environmental stress, could result in large and unpredicted outbreaks of exotic insects and diseases.

Responses of Forest Vegetation to Climate Change

Forest species composition and growth, respectively elements of forest structure and forest function, are sensitive to climate. Climate affects forest growth rates in large part through growing season length, availability of soil moisture, and temperatures at which photosynthesis and respiration take place. In comparison, species composition responds to climate by effects on survival of existing trees in mature stands, flowering and seed production, and survival of germinated seedlings. However, the long time between stand establishment and replacement of most northern tree species means they will be increasingly less well adapted to local conditions as climate change progresses (Aitken and Hannerz 2001).

Potential climatic disequilibrium of species with environment can be evaluated using climate envelopes (e.g., Shafer et al. 2001, McKenney et al. 2007). With this approach, the current climate in which a species grows is described in terms of climate values such as summer or winter temperature, growing season precipitation, and growing degree days. The future location of a species' climate envelope after a period of climate change is then compared with the present one. McKenney et al. (2007) found that the major changes in climate predicted for coming decades could result in many North American trees growing outside their climate envelopes. Other researchers have found similar results: In most cases species'climate envelopes are projected to move north and to move mostly or entirely beyond the current range (e.g., Iverson and Prasad 2002, Iverson et al. 2005, Malcolm et al. 2005, McKenney et al. 2007).

Even the lower ranges of predicted warming and drying could affect the composition and productivity of forests, such as in northern Michigan, where such changes could cause decline in several commercially valuable tree species (Reed and Desanker 1992). According to Graham et al. (1990), increasing summer temperature in the Great Lakes Region would move the present climatic envelope hundreds of kilometres north. The southern range

limits of sugar maple (*Acer saccharum* Marsh.), trembling aspen (*Populus tremuloides* Michx.), balsam fir (*Abies balsamea* (L.) Mill.), white birch, white spruce (*Picea glauca* (Moench) Voss), black spruce, jack pine, and red pine (*Pinus resinosa* Ait.) to the north is about halfway up the lower Michigan Peninsula, and in Ontario there is a transition from these species along a line running across southwestern Ontario roughly from Grand Bend (near Sarnia) to Toronto. South of this line, species such as silver maple (*Acer saccharinum* L.), shagbark hickory (*Carya ovata* (Mill.) K.Koch), black walnut (*Juglans nigra* L.), yellow poplar (*Liriodendron tulipifera* L.), sycamore (*Platanus occidentalis* L.), and black oak (*Quercus velutina* Lam.) are more common. As the climate warms, the faster-growing, less cold-hardy species to the south of these lines in Michigan and Ontario could slowly migrate north, each at a unique rate (Reed and Desanker 1992).

Changes in climate envelopes for western Upper Michigan are also expected to favour southerly species within less than 100 years. Again, slow rates of natural migration mean these species will be unable to exploit the potential new range (Solomon and Bartlein 1992). For example, the climate envelope for butternut (*Juglans cinerea* L.) will move to western Upper Michigan within 70 years, but the nearest butternut are about 90 km south. Based on historic migration rates, these butternut populations are about 450 migration years away. White oak (*Quercus alba* L.) and black oak will be in a similar situation, with warming predicted to move their climate envelopes into western Upper Michigan within 150 and 200 years, respectively, while these species would require 200 and 500 years, respectively, to migrate (Solomon and Bartlein 1992).

Most studies of climate envelope movement predict that tree migration will be slower than envelope movement (Tallis 1991, Iverson et al. 2002, McLachlan et al. 2005). Movement of more southerly tree species into Ontario will also be slowed by physical barriers such as the Great Lakes and the large areas of farms and cities in the United States and southern Ontario, as well as the fact that populations of Carolinian species in southern Ontario are small and isolated. Even existing forests can hinder migration, since many tree species do not regenerate under a forest canopy.

Forest Growth

Each tree species is uniquely affected by responses to climate based on its ability to respond to increased (or decreased) soil moisture and nutrient availability, and disturbance frequency. For example, Goldblum and Rigg (2005) modelled the potential change in growth rates of 3 tree species – sugar maple, white spruce, and balsam fir – at the margin of the Great Lakes-St. Lawrence and boreal forest regions in Ontario. Their results showed that sugar maple will likely increase growth the most, with a smaller increase for white spruce. Balsam fir was projected to have decreased growth.

Climate envelope movement can overestimate effects of climate change on growth of widely distributed species. Trees from local seed sources are usually considered best adapted to local climate because their growth cycle should be more attuned to climatic cues (Wright 1979). However, this principle may not always apply to widely distributed species. For example, lodgepole pine populations near the northern species limit in British Columbia grow at temperatures that are up to 7°C colder than is optimum for growth (Rehfeldt et al. 1999); growth of these populations should increase with climate warming. However, nearer to the centre of its range, in southern British Columbia, lodgepole pine populations fit the "local is best" concept, growing in climates only 0.5°C below their optimal temperature. Here climate warming will result in local populations being increasingly maladapted, decreasing growth (Rehfeldt et al. 1999).

Where drought increases, competitiveness and growth rates of moisture-loving species could fall, favouring the transition to more drought-resistant ones. However, elevated CO_2, which increases drought resistance, will offset drought effects of climate change to some extent. Occasional episodes of hot, dry conditions could lead to rapid regional decline of some species (Parker et al. 2000) and increase the incidence of damaging disease and insect infestations. Such an event occurred in the early 2000s, when pinyon pine (*Pinus edulis* Engelm.) in the U.S. Southwest experienced extensive mortality over a 15-month period due to low soil moisture, which favoured a bark beetle infestation (Breshears et al. 2005).

Increasing atmospheric CO_2 apart from changes in climate will affect growth in the short term and alter species abundance and population genetic makeup. Early successional species (e.g., raspberry (*Rubus)* and grasses) react more aggressively to disturbed areas and have a larger increase in growth under elevated CO_2, and their short life cycles allow more rapid genetic adaptation to changing climate (Körner 1993). More aggressive competition may hinder regeneration of trees. Lindroth et al. (1993) found that trembling aspen, red oak (*Quercus rubra* L.), and sugar maple, in that order, increased dry matter growth under elevated CO_2, indicating the potential for species' competitive abilities to change as greenhouse emissions rise. Analysis of over 500 studies on the effect of elevated CO_2 on woody plant growth described large positive plant responses, ranging from a growth reduction to a five-times increase relative to plants grown at ambient CO_2 levels (Curtis and Wang 1998); across all the studies they assessed, biomass increased significantly at about double ambient CO_2, with an average increase of 31%.

Increased CO_2 can also affect competitiveness within a species. For example, Houpis et al. (1999) found that photosynthetic increases in ponderosa pine (*Pinus ponderosa* Laws.) populations varied from 19% to 49%. However, in black spruce (Johnsen and Major 1998) and jack pine (Cantin et al. 1997), the most common conifers in Ontario, CO_2 increased growth of all populations but did not alter their relative rankings. In contrast, elevated CO_2 altered competitiveness among trembling aspen clones (Lindroth et al. 2001, Tupker et al. 2001).

Increasing temperature could favour growth of northern forests by increasing photosynthesis. However, the extent of growth increases will depend on the mineralization of additional available nitrogen, which often limits photosynthesis (Saxxe et al. 2001). Many models predict that climate change and increasing CO_2 in the atmosphere will increase global forest growth over the next 50-100 years, especially at higher latitudes. However, increased rates of forest disturbance will reduce forest growing stock and offset gains from potential growth increases (Saxxe et al. 2001).

Several large-scale analyses have focused on how climate change will affect forest productivity, including Joyce and Nungesser (2000), who predicted forest productivity in the United States will increase under elevated CO_2. However, these researchers noted that where moisture stress or low nutrient availability occur, productivity increases will be constrained. They projected changes in productivity using 2 global climate models (OSU, the Oregon State University model and GFDL-Q, the Geophysical Fluid Dynamics Laboratory Q-flux model). Using outputs from both GCMs, the effects of changes in temperature and precipitation projected under climate change in 2044 with CO_2 at 625 ppm are predicted to increase growth 20-40% in northeastern and Lake States forests in the United States, near the southern border with Ontario.

In another U.S. study, Jenkins et al. (2000) used 2 forest productivity models to examine potential effects of climate change. Climate change and elevated atmospheric CO_2 were projected to cause "very large increases in forest NPP" in the northeastern U.S. However, similar to Joyce and Nungesser (2000), actual gains will be more modest because of limitations of forest soil nutrients, the effects of pollution by acid rain and ground-level ozone, and, on some sites, water stress due to inadequate precipitation.

Species Composition

Many boreal species can survive in temperate climates (Loehle 1998), indicating that southern species limits do not necessarily relate to maximum summer temperatures. Species distributions reflect a tradeoff between height growth rate and tolerance of cold temperatures (Loehle 1998). Thus, at southern range margins, most species are not limited by high temperatures but are instead outcompeted by faster-growing species. At northern range margins, the effects of temperature on flowering, seed set, and seedling survival may determine species success rather than maximum winter frost resistance of leaves and buds (Bannister and Neuner 2001). Increasing minimum winter temperatures will allow more southerly, faster-growing species to migrate north. As stated by Loehle (1998): "The implication for future climate change is that forests will not suffer catastrophic dieback due to increased temperatures but will be gradually replaced by faster-growing types, perhaps over hundreds of years."

Changes in tree species composition on a landscape usually occur slowly, even though species composition at a stand level can occur quickly following disturbance or over the course of several growing seasons in response to drought or insects. One reason landscape-level changes are slow is that even in fire-prone parts of the boreal forest the annual rate of forest disturbance may only be 1% per year, part of which would return to its pre-disturbance composition. A 1% disturbance rate means that after 30 years of altered climate, composition of the remaining 70% of the forest would tend to be unaltered

Following forest disturbance an opportunity exists for regeneration of a different mix of tree species than was in the preceding stand. Under current climate, species regeneration success can depend on the ability to survive high levels of environmental stress; climate change is liable to intensify stress from high temperatures and drought producing inter-species and genetic pressure on regenerating trees and other plants. Seedlings occupy a narrow physical zone just above the ground (Figure 5), where environmental conditions create selection pressures on seedlings (Colombo 1996). Highest temperatures on sites disturbed by fire and harvest usually occur within a few centimetres of the soil-air interface due to the soil absorbing heat from the sun (Geiger 1965). Temperatures usually decline sharply to more moderate levels in the air above the surface and below ground. As trees grow, their buds and foliage are no longer in this maximum heat zone, reducing stress. Therefore, heat stress will affect seedlings more than older trees as climate change increases temperatures.

Desiccation is also a problem for young trees, which have small root systems tapping small soil volumes. Young plants' roots tend to reside exclusively in the upper horizons of the soil, the area that is usually driest and hosts the most intense competition for water. As trees grow, much of the root system remains near the soil surface, but the root system grows wider and usually deeper, increasing access to soil moisture and reducing the likelihood of water deficits (Figure 5).

In addition to having limited root systems, seedlings inhabit the high temperature/high vapour pressure saturation deficit zone just above the soil surface, increasing transpirational water loss and desiccation risk. As trees grow, shoots extend up to cooler zones, where air drying is usually lower, reducing transpiration and desiccation. Windiness is usually greater further above ground, which increases transpiration but also cools the foliage. As the crown closes, windiness within the canopy drops, reducing drying.

Although climate change is likely to favour regeneration of more heat and drought tolerant species, regenerating species can only come from those whose seeds or suckers (in the case of aspen) are able to reach the site of forest disturbance. Seed dispersal distances for Ontario species provided by Burns and Honkala (1990) indicate that the majority of seed for any tree species falls within <100 m of the parent tree. So, some mixture of the species present near a forest disturbance is most likely to regenerate. Climate change may affect composition of regenerating stands by altering flowering and seed production and by creating a hotter, drier seedling environment.

In contrast to stands affected by canopy-removing stand disturbance, some stands become overmature and canopy gaps formed as older trees die are filled by shade tolerant trees from the understory. However, understory temperatures are buffered by the remaining canopy and other understory vegetation. Consequently, this form of forest succession provides less opportunity for natural adaptation to climate change to take place by selective pressure on seedling survival, compared to strong selective pressure when seedlings regenerate disturbed sites.

In the case of non-disturbance forest succession, tree species and within-species genetic composition will lag behind climate in what is termed *vegetational inertia* (Cole 1985, Lewin 1985), which can allow a plant community to remain long after the climate the community was established in has changed (Lewin 1985). Unless affected by a stand-replacing disturbance (Kullman 1989), such out-of-synch communities will tend to persist since dominant species can exclude competitors and affect microenvironment (e.g., light, moisture, soil chemistry) to their favour. The time lag for vegetational change depends on growth rate during reproduction of a potentially migrating species compared with the resident species, the availability of seed and seedbed, and the difference between the prevailing climate and a species' climate envelope (Lewin 1985).

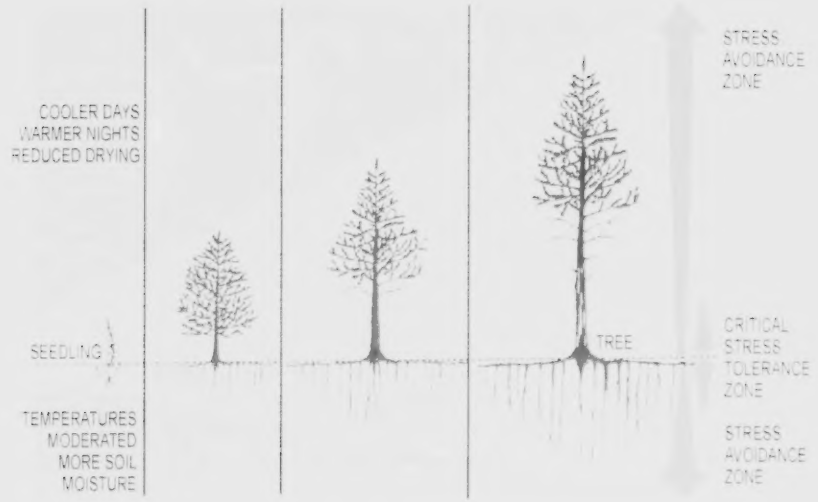

Figure 5. *Environmental stress exposure during tree establishment. Smaller plants occupy the air/soil interface where temperatures and moisture fluctuate most exposing them to water deficits, freezing, and high temperatures. (From Colombo 1996)*

Silviculture in a Changing Climate

Disturbance by fire, insects, and disease will probably be the largest and most immediate effects of climate change. Increased fire frequency in particular could affect silviculture by reducing average stand age and wood availability and by creating opportunities for southern species to migrate naturally or to be introduced by planting (i.e., assisted migration). In addition, Rehfeldt et al. (1999) concluded that "there seems little doubt that maintaining forest productivity in the face of global warming would require human intervention to assist the migration of genotypes to their most suitable climates."

Harvest Rates

Climate change can affect harvest rates in at least 3 ways:

1. Maintaining a desired stand age distribution or total area of disturbance may require adjustment of fire and forest management strategies if risk of natural disturbance changes.
2. Forests at high risk of loss to disturbance or general decline could be harvested before reaching their otherwise optimal rotation age, allowing replacement by better-adapted species or populations and permitting utilization and capture of carbon in forest products.
3. Salvage harvesting on disturbed areas may be considered to meet wood supply needs.

As climate change causes species and populations to be less well adapted to local conditions, disturbance will provide an opportunity to plant better-adapted species and populations or to allow natural selection during regeneration to favour more adaptable species. Disturbance in general can help forests adapt to a changing climate, but stands at increased risk of forest fire, insect infestations, or disease could, in certain cases, be harvested to allow the use of the wood. Such a strategy could be important to improve adaptedness of commercial species with long harvest cycles, which will be increasingly at risk as climate change progresses during their long life spans (Singh and Wheaton 1991).

Milder winters and increased freeze-thaw activity will likely create problems for winter forestry operations, especially logging and hauling, in areas dependent on frozen ground and watercourses (Pollard 1989). Logging and hauling could be shut down during the winter, or winter harvesting could be shortened due to later freeze-up and earlier thawing. The response could be to construct more all-weather logging roads, which have a greater ecological impact on forests than winter roads do and cost more (Pollard 1989).

Wood Supply

In Ontario and most other jurisdictions, growth of commercial forests is predicted by examining the historical relationship between a species' growth rate and tree age in a particular forest region or district. Merchantable volumes are predicted using yield tables constructed from historical tree and stand growth data. However, because trees live so long, size-based measurements reflect the average growth response to past climate and site conditions. Forests more than 150 years old regenerated during the colder conditions of the Little Ice Age (Gillson and Willis 2004); thus, predictions of future forest growth based on historic growth will be increasingly inaccurate as the climate changes.

Today's forest managers need forest growth projections that incorporate the effects of climate change and elevated CO_2. Developing such predictions requires an approach that is not based on the premise of a static environment and historical growth rates. One option is to use process-based, climatically driven growth and yield models such as TRIPLEX, which account for changes in environment (Peng et al. 2002). With TRIPLEX, empirical forest growth and yield models are modified by combining them with data on environment (monthly mean temperature, soil moisture availability, and length of the frost-free period), allowing them to produce wood supply projections that are related to climate change scenarios.

Warming and longer growing seasons may make some forested areas with productive soils more suitable for farming; converting these areas to farmland could decrease forest area, as could increased forest fire and drought. Some parts of Northwestern Ontario, where forests may change from conifer- to aspen-dominated stands or from aspen stands to aspen parkland or grassland (Hogg and Bernier 2005), are particularly at risk. At the southern edge of the boreal forest of western interior Canada, where some species already regenerate with some difficulty, intermittent forests may be reduced further (Singh and Wheaton 1991, Hogg and Bernier 2005). Such changes in the amount of forested land would in turn affect wood supply.

Future silvicultural efforts should concentrate on forested sites likely to remain productive despite climate change (Singh and Wheaton 1991). For example, fast-growing genotypes should be planted mainly in areas not expected to experience frequent drought as the climate changes. Silvicultural practices that increase water availability, such as thinning and competition control during regeneration (Parker et al. 2000), could be encouraged if moisture stress is an issue, as could planting drought-tolerant species (Papadopol 2000).

Genetics and Regeneration

Species or provenances growing outside their climate envelope are more susceptible to competition, predation, disease, and fire (Pollard 1989). In this way, natural forces tend to maintain better-adapted species and populations (Pollard 1989). According to Hepting (1963), "if the probability of the relation of climatic influences to certain tree declines is appreciated by foresters…we are more likely to plan our silviculture to encourage or to plant unaffected species or geographic races of the declining species that are better adapted to the newer climate."

To what extent should species or genotypes from more southerly sources be planted further north to better match future climate conditions? Rehfeldt (2000) was of the opinion that to avoid large reductions in wood production, forest managers will need to plant climatically adapted populations. Planting to transfer appropriate genotypes between seed zones or introducing new species can accomplish climatic adaptation in one generation what nature would need several generations to do (Singh and Wheaton 1991, Rehfledt 2000).

Planting nursery stock north of its current seed zone to try to match a future climate may or may not increase future timber yields but can carry immediate risk from freezing damage (Ledig and Kitzmiller 1992, McLachlan et al. 2007). Natural selection has resulted in shorter growing cycles to avoid damage from late spring and early fall frosts. Thus, local populations do not take full advantage of the growing season in average years. Transferring populations north will increase yields in future but at present risks exposing trees to freezing damage due to the tendency of southern populations to remain active later in the growing season and to resume growth sooner. Ledig and Kitzmiller (1992) suggested addressing this risk using the "diversity principle": by planting local seed sources mixed with some expected to be better adapted to climate change. The relative amounts of each seed source in the mixture would depend on the degree of certainty of projected climate changes.

The other problem with moving seed sources northward is they may not be matched to local daylength (Ledig and Kitzmiller 1992). The longer photoperiods during the growing season at more northerly latitudes could cause trees to remain active later, making them more susceptible to fall frosts. Ledig and Kitzmiller (1992) suggest that photoperiod might not be a factor if moving seed 150 to 300 km northward. However, Singh and Wheaton (1991) suggest that each 1°C increase in temperature in North America will translate into a range change of 100 to 150 km. Based on the A2 scenario and the Canadian GCM, by mid-century most of Ontario is projected to experience average temperature increases of 3-5°C in summer and 5-8°C in winter (Colombo et al. 2007b). Thus, to match temperature seed would need to be moved 400 to 600 km north, but this would result in mismatching of populations with photoperiod.

Ensuring genetic diversity of planted forests will be important to allow species to adapt to their new environment and be able to perform moderately well in a range of conditions. Climate and atmospheric CO_2 will likely change beyond the end of this century, and the nature of change over even the next several decades is uncertain. In addition, forest managers must be prepared to plant at higher than historic rates, to assist the slow natural redistribution of genotypes (Rehfeldt 2000).

Forest managers often rely on natural regeneration to produce new forests after disturbance. For example, much of the area burned by forest fire regenerates readily from seed or sprouts of local origin. However, if climate change means local populations are no longer optimal, then increased planting might be used to introduce better-adapted populations. Given the predicted speed of climate change, artificial regeneration will be needed to grow new forests where they are climatically well adapted (Rehfeldt 2000). Seed collection efforts will need to increase to support increased planting (Cherry 2001), especially for species with seed that does not store well. Species will vary in how much help they will need to adapt to new climate conditions (Parker et al. 1999). Widely distributed species, which are usually more genetically diverse, should adapt to some extent through natural selection. However, adaptation pressure is greatest during regeneration (Figure 5; Colombo 1996). Therefore, even widely distributed species may require intervention through planting selected genetic sources in new areas and conserving and propagating genotypes adapted to potential future climates (Rehfeldt 2000).

Rehfeldt (2000) pointed out that deciding how to renew forests under climate change is complicated by the need to adjust not only *what* to do but also *when to begin doing it*. He argues that it is not too early to begin adjusting seed deployment by transferring genotypes from warmer provenances to cooler ones. A simpler approach might be to mix seed from different zones and to allow natural selection to take place (Ledig and Kitzmiller 1992, Rehfeldt 2000). As already noted, assisted migration of genotypes and species according to climate change predictions should reflect social, technical, and scientific input. Foresters should begin soon to develop scenarios for allocating nursery stock that will allow them to deploy provenances and species based on projected rather than historical climate zones. However, they must recognize the risks of acting on such scenarios, especially if contemplating introducing non-native species. Before planting nursery stock outside their current climate zones, a key step would be to ensure such movement is based on peer-reviewed science. One means of doing so is to submit proposals to an expert panel with a mandate of respecting the precautionary principle while permitting pilot projects that improve understanding of the risks and benefits of implementing adaptations (McLachlan et al. 2007).

Carbon-based Forest Management

In 2007, the Fourth Assessment Report by the IPCC stated that "in the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre, or energy from the forest, will generate the largest sustained mitigation benefit" (IPCC 2007b, Chapter 9, Page 543.).

Some forest activities increase carbon storage, while others release carbon to the atmosphere or are carbon neutral. Deforestation caused by forest access roads, for example, releases carbon to the atmosphere from the increased decomposition of organic matter removed to construct the road, and more important, from reduced carbon sequestration by creating areas that no longer grow trees (Colombo et al. 2005). In contrast, planting increases carbon sequestration compared to natural regeneration from seed, if it allows faster establishment of tree cover and greater likelihood of full stocking. Carbon in forests must be considered in context with net greenhouse gas exchange with the atmosphere, including emissions from forestry activities, carbon stored in wood products, and avoided emissions when wood products are used in place of more energy-intensive alternative fuels or materials. Overall, harvesting forests at a rate that maintains the standing forest stock, combined with an increasing stock of wood products, results in net removal of CO_2 from the atmosphere (Tonn and Marland 2006).

Ontario's managed forests were estimated to contain 6.19 billion tonnes of carbon in 2000 (Colombo et al. 2007a), the equivalent of 22.72 billion tonnes of CO_2. These forests are projected to increase carbon storage by 69.4 million tonnes between 2000 and 2100, or about 0.7 million tonnes per year (Colombo et al. 2007a). When carbon in wood products is included, storage increases to 433.8 million tonnes of carbon between 2000 and 2100 (Colombo et al. 2007a, Chen et al. 2008). This increase equates to an average removal of 15.9 million tonnes of CO_2 from the atmosphere annually.

Energy used to create wood products results in some carbon emissions, but projections for Ontario show that these emissions are much less than the overall net reduction in atmospheric greenhouse gases from sustainable forest management and the use of wood (Colombo et al. 2007a). Emissions from transporting wood to mills and burning fossil fuels during manufacturing were estimated to be roughly 9% of the amount of carbon stored in wood products from Ontario (Colombo et al. 2007a).

In addition, using wood products produces important indirect reductions in greenhouse gas emissions. For example, wood from sustainably managed forests used as a biofuel is carbon neutral, and the energy generated reduces the need to burn fossil fuels (Gustavsson et al. 1995). When wood is used to replace building materials such as steel, aluminium, bricks, and concrete, which require more energy and thus emissions to produce, greenhouse gas emissions are reduced (Eriksson et al. 2007, Sathre 2007). In a review of building materials used in Scandinavia, wood construction consistently resulted in lower greenhouse gas emissions than did other materials (Petersen and Solberg 2005).

Increasing carbon storage in Crown forests could be accomplished by adjusting policies and allocating funding to promote silvicultural practices that increase carbon sequestration, such as tree planting (Richards et al. 1997). Government policy affects most Ontario and Canadian forests, since most managed forest is publicly owned. Governments can provide incentives to encourage carbon storage on private land, including subsidies for carbon sequestered, and the creation of a market for stored carbon (Richards et al. 1997). In 2007, the Ontario government used one such tool, when assistance for afforestation was announced to plant 50 million trees by 2020 on private land in the southern part of the province (UNEP 2007).

Several researchers have considered how taxes or subsidies for carbon stored in forests could affect forest economics (e.g., Binckley and van Kooten 1994). However, disregarding carbon storage in wood products and the reduced emissions from using wood in place of fossil fuel or energy-intensive building materials provides an incomplete and misleading picture of overall effects of such incentives. As Binkley and van Kooten (1994) pointed out, forests and people benefit when governments use carbon taxes to promote carbon storage in forests, as well as materials policies that lengthen the lifespan of wood products and promote use of wood products over those manufactured from more energy-intensive materials (Binckley and van Kooten 1997, Lippke et al. 2004, Gustavsson et al. 2006).

Managing forests for the highest overall carbon storage, including wood products, is an important issue confronting foresters. Public concern about how forestry practices affect national and global carbon stocks is increasing, as predicted by Pollard (1989). Sustainable management of forests for multiple social and ecological benefits, of which timber production is one, is now common practice in Ontario and the rest of Canada. The IPCC (2007b) states that sustainable management that maintains forest carbon stocks and produces sustained yield of wood products is the most effective strategy to use forests to mitigate climate change. Forest managers and the public overall need to understand that future sustainable forest management may have to include harvesting timber and creating wood products as part of a suite of activities designed to promote tree species adaptation to new conditions, increase forest carbon storage, reduce emissions, and slow climate change.

Conclusions

Early in this paper, I described a scenario in which forests are exposed to an environment that has not existed for at least 100,000 years. Only a few decades ago, many people would have viewed this scenario as science fiction, but now evidence is growing that this rapid climate change is underway. Under some projections, in the time it takes for a typical forest rotation, climate change would cause average temperatures in Ontario to rise up to 5°C warmer in summer and 9°C warmer in winter, with CO_2 levels tripling. Forest managers potentially will face many challenges under such rapid change, including increased forest fires, severe unexpected insect infestations and disease outbreaks, and forest decline due to drought. They may also see some benefits, such as increased tree growth where moisture and nutrients are not limiting.

Evidence suggests that we are now seeing climate change effects, and experts are predicting that climate change will result in large-scale ecosystem change. However, so far forest management is still based on a constant-climate paradigm (Parker and Colombo 2003). As McLachlan et al. (2007) state: "We… strongly reject the…ubiquitous 'business as usual' scenario that is the current de facto policy." Given the inevitability of climate change and the potential effects of it and elevated atmospheric CO_2, it is imperative to consider how such changes will affect forests and forestry and how forest management can adapt. Adaptation and mitigation options discussed in this paper are shown in Table 1.

Debates about how and when to adapt to climate change will continue, but most governments are no longer reticent about the need to incorporate climate change into forest management decision-making. Now that climatologists are making more confident assertions about the likelihood of climate change and governments are starting to act to control greenhouse gas emissions, the following question is taking on increased urgency: When will it be appropriate for foresters to discard the constant-climate paradigm and intervene to adapt forests to the changes that are underway?

Clearly, they must begin acting soon, since many of their decisions affect forests for 50 or more years, during which time the climate will change. For action to take place, foresters, biologists, and other resource managers need clear direction to involve them in developing management techniques that identify and reduce harmful impacts of climate change. These activities need to be coordinated and carefully thought out, and they will require policies that link well-planned research with field-testing of adaptive measures. To develop such policies, governments need a better understanding of the response of forests to environment as well as models that use such information to project future forest condition. This work will help define levels of uncertainty and guide forest managers as to when and how to intervene to reduce risks of climate change impacts.

Table 1. *Some potential climate change strategies for forest adaptation and climate change mitigation.*

Have multi-disciplinary panels of local experts and scientists develop adaptation options, prioritized by risk (high, moderate, low) and scale of implementation area (large, medium, small)
Alter harvest rates 1. Adjust fire and forest management strategies to maintain desired stand age distribution and total area disturbed if rates of natural disturbance change 2. Consider harvesting forests at high risk of loss to disturbance or general decline before they reach their otherwise optimal rotation age, to allow better-adapted species or populations to move in and permit utilization/capture of woody carbon in forest products 3. Consider salvage harvesting in disturbed areas to meet wood supply needs
Construct more all-weather logging roads to address shortening of the period of winter harvesting due to later freeze-up and earlier thawing
Develop forest projections that incorporate the effects of climate change (and elevated CO_2) on growth rates
Apply silviculture to optimize return on investment 1. Concentrate silvicultural efforts on forested sites likely to remain productive despite climate change 2. Plant drought-tolerant species on drier sites 3. Plant fast-growing, genetically improved trees in areas not expected to experience frequent drought 4. Use silvicultural practices that increase water availability, such as competition control during regeneration
Plant seed from local sources with some that are expected to be better adapted to the changing climate
Maintain high levels of genetic diversity
Increase planting rates to assist slow natural redistribution of genotypes and species
Harvest forests according to the principles of sustainable forest management, using wood products as biofuel and building materials

Forest management decisions based on future rather than past climate information should increase forest sector carbon while reducing potential impacts of climate change. Implementing such strategies in the short term will not only help mitigate climate change but also expand markets for a forest industry presently facing serious economic challenges. New products could include those that replace more energy-intensive materials such as concrete and steel as well as wood-based biofuels (Ter-Mikaelian et al. 2008). Forestry should play a role in reducing climate change through increasing carbon storage and helping decrease emissions in other sectors.

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